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MODELING OF STRENGTH AND TOUGHNESS OF CERAMIC MATRIX COMPOSITES BASED ON DISCRETE FIBER DISTRIBUTION

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13. ABSTRACT *(Maximum 200 words)*

The prime objective of the project was development of a practically reliable model that would help to understand of the process taking place and the mechanics of failure development in ceramic matrix composites. During the course of the project, we developed a micromechanical model which could address a variety of aspects of the composite behavior on macroscale. The model uses the mechanical properties of composite components, interfaces, and their interactions on microscale to address the resulting macromechanical behavior of the composite. Our approach was based on a recently developed effective analytical method for analysis of failure development in composites using a discrete distribution of the reinforcing components. This new method enabled us to extract the information essential for fracture analysis from the composite system at any intermediate step of failure development, and to evaluate the specific contribution by each reinforcing component in the composite. This analysis of a composite system using discrete fiber distribution allows an optimization of the composite system for the most desirable mechanical properties. In the course of this project, we successfully developed this methodology for application to ceramic matrix composites reinforced by unidirectional fibers, extended the analytical development for application to a ceramic matrix reinforced by ductile particles, and developed the analysis of a variety of other composite systems, including metal matrix composites.

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OBJECTIVES:

The prime objective of the project was development of a practically reliable model that would help to understand of the process taking place and the mechanics of failure development in ceramic matrix composites. During the course of the project, we developed a micromechanical model which could address a variety of aspects of the composite behavior on macroscale. The model uses the mechanical properties of composite components, interfaces, and their interactions on microscale to address the resulting macromechanical behavior of the composite. Our approach was based on a recently developed effective analytical method for analysis of failure development in composites using a discrete distribution of the reinforcing components. This new method enabled us to extract the information essential for fracture analysis from the composite system at any intermediate step of failure development, and to evaluate the specific contribution by each reinforcing component in the composite. This analysis of a composite system using discrete fiber distribution allows an optimization of the composite system for the most desirable mechanical properties. In the course of this project, we successfully developed this methodology for application to ceramic matrix composites reinforced by unidirectional fibers, extended the analytical development for application to a ceramic matrix reinforced by ductile particles, and developed the analysis of a variety of other composite systems, including metal matrix composites.

RESULTS OF EFFORT:

During the course of the project, we developed an analytical method which allowed us to form exact analytical solutions for a set of basic problems which represent essential microstructural models describing the crack growth in reinforced ceramic matrix composites. The method uses the analytic functions theory and its applications to the theory of elasticity coupled with special physical effects created by the reinforcements. The developed method enables us to consider the process zone geometry as a discrete distribution of the reinforcing components, without necessarily smearing the actions by fibers or particles along the crack surfaces, the step which usually limits the effectiveness of a model. Using this approach we were able to examine several basic cases of fiber pullout relationships. We investigated a single fiber model which allowed us to evaluate the fundamental aspects of the reinforcement mechanism taking place in ceramic matrix composites.

We analyzed resistance curves for different systems of composites when the fiber pullout relationship is controlled. This type of information may guide the composite designer in developing the most efficient composite systems. Thus, for example, the case of fiber pullout under a constant force does not appear to be effective in developing fracture resistance in the composite. The case of nonlinear fiber pullout is effective for short distances between the fibers; for large distances, it may be treated as a linear case. This information is very useful for practical applications.

The effect of fiber spacing was also evaluated for the case of the linear fiber pullout relationship. The results demonstrate that it is possible to fabricate a composite with the most effective composite toughness and fracture resistance by using optimal fiber spacing.

We also extended our analytical approach to the case of the ceramic matrix reinforced by ductile particles. We developed a model for discrete particle distribution within the bridging zone. The analysis explicitly involves the particle spacing, the strength of the particle-matrix interface, particle ductility, and the effect of the particle size. The model we developed may find several applications in other material systems. For example, a fracture model for new metallic materials may be developed using very similar ideas and mathematical methodology as in the developed model. These new materials were recently developed and currently are under investigation for possible application to aircraft structure, as light structural materials.

In the course of the project, a general model was developed for the analysis of the fracture process in composites with a more general constitutive behavior of the matrix. As an application of the method, the metal matrix composite system was considered. This composite system consisted of an elastic - ideally - plastic matrix reinforced by elastic, typically ceramic, fibers. The model revealed several interesting physical aspects of the reinforcement mechanism in these composites. Because of the compatibility restrictions, the plastic yield of the matrix could not take place near the fibers, and therefore must be confined to the line-like process zone. The model could predict formation of voids within the process zone and evaluate corresponding fracture resistance development. This modeling technique could be applied to a broad class of fiber reinforced composites with nonlinearly behaving matrices.

ACCOMPLISHMENTS AND NEW FINDINGS:

The main accomplishment of the project is development of a new analytical method for failure analysis in composites, applying this method to special cases is important for air force applications. The method is based on the analytical principles of the theory of elasticity coupled with specific conditions imposed by the reinforcing fibers or particles. The developed framework for failure analysis in composites includes complete characterization of the set of physical processes taking place within the failure process zone. In particular, the method explicitly includes in the analysis a detailed description of the activities along the fiber-matrix, or particle-matrix interfaces. The distinctive aspect of the developed method is its ability to treat the discrete fiber, or particle distribution within the system. These qualities of the formulated framework allow one to conduct a detailed investigation of the reinforcing mechanism and fracture resistance development in the composite systems. It allows optimization of composite properties by manipulating the interface properties and the distribution of the reinforcing components.

The method was applied to failure analysis in fiber reinforced ceramics, particulate reinforced ceramics, and fiber reinforced metal matrix composites. The details of the analysis for these composite systems can be found in the publications listed below which resulted from this project. The principal publications are attached to this report.

PERSONNEL SUPPORTED:

Principal investigator: Asher A. Rubinstein

Research Assistant: Peng Wang.

Mr. P. Wang was supported during his studies toward the Ph. D. degree at Tulane University. In !998, Mr. P. Wang completed all course requirements and his dissertation, and received his degree.

PUBLICATIONS:

- Rubinstein, A. A. "Influence of the Interface on the Strength and Toughness of Composites." (Submitted for publication)
- Rubinstein, A. A., "Remarks on Macrocrack - Microcrack Interaction and Related Problems." *International Journal of Fracture,* Vol. 96, pp. L9 - L14, 1999.
- Rubinstein, A. A., "Strength and Toughness Modeling of Advanced Composites." *Applied Mechanics in the Americas*, Vol. 7, (P. B. Goncalves, I. Jasiuk, D. Pamplona, C. Steele, H. I. Weber and L. Bevilacqua Editors) pp. 711 - 714, Published by AAM and ABCM - Rio de Janeiro, Brazil, 1999.
- Wang, P., Micromechanical Analysis of Failure Development in a Class of Composite Materials. Ph. D. Dissertation, Tulane University, 1998.
- Rubinstein, A. A. and Wang, P., "Micromechanics of Failure in Metal Matrix Composites." *Transactions of the CSME,* Vol. 22, No. 4B, pp. 457 - 466. 1998.
- Rubinstein, A. A., "Fracture Analysis of Composites by a Micromechanical Approach" *Composites Science and Technology*, 58 (1998) 1785 - 1792.
- Rubinstein, A. A. and Wang, P., "Micromechanical analysis of failure in metal matrix composites." CSME Forum SCGM 1998, Vol. 2, pp. 71-76, Ryerson Polytechnic University, Toronto, Ontario, Canada, 1998.
- Rubinstein, A. A. and Wang, P., "The Fracture Toughness of Particulate-Reinforced Brittle Matrix." *Journal of the Mechanics and Physics of Solids.* Vol. 46. No. 7, pp. 1139 - 1154, 1998.
- Rubinstein, A. A., "Strength and Toughness Modeling of CMC Based on Discrete Fiber Distribution." *Air Force Office of Scientific Research. Mechanics and Materials Program Review* pp. 59 - 63, AFOSR, Directorate of Aerospace and Materials Sciences, 1997.
- Rubinstein, A. A., "Micromechanical Approach to Failure Process in Composites.[1]" *Advances in Fracture research.* (B. L. Karihaloo, Y-W. May, M.I. Ripley and R. O. Ritchie, Editors) ICF9 Sydney Australia, Vol. 2, pp. 631-642. Pergamon, 1997.
- 32. Rubinstein, A.A. and Wang, P., "Brittle Matrix Toughening by Ductile Particles." *Applied Mechanics in the Americas*, Vol. 4, (L.A. Godoy, M. Rysz, L.E. Suáres, Editors), pp. 85-88, The University of Iowa, Iowa City, IA, 1997.
- 31. Rubinstein, A. A. and Wang, P., "Failure Development in Particulate Composites." AD-Vol. 51/MD-Vol. 73, *Proceedings of the ASME Aerospace and Materials Divisions*, (Editors: W. S. Chan, M. L. Dunn, W. F. Jones, G. M. Newas, P. V. D. McLaughlin and R. C. Wetherhold) Book No. G01026 - 1996, pp. 415-425, ASME, New York, 1996.
- 30. Rubinstein, A. A., "Analysis of Selected Failure Modes in Composite Materials." Technical report for Martin Marietta Manned Space Systems, December, 1995.
- 29. Rubinstein, A. A., "Essential Aspects of Unidirectional Fiber Reinforcement in Ceramic Matrix Composites." *7th International Conference on Mechanical Behaviour of Materials*, pp. 237-238, Edited by A. Bakker. Delft University Press, The Netherlands, 1995.
- 28. Rubinstein, A. A., "Micromechanical Analysis of Strength of Fiber Reinforced Brittle Matrix Composites." *Applied Mechanics in the Americas* Vol. III, pp. 273-278. (Edited by L. A. Godoy, S.R. Idelson, P.A.A. Laura and D.T. Mook, AAM and AMCA, Santa Fe), Buenos Aires, Argentina, 1995.

[1]Keynote lecture at The Ninth International Conference on Fracture. Sydney, Australia, April 1-5, 1997.

INTERACTIONS/TRANSITIONS:

a. Participation/Presentations at meetings, conferences, seminars, etc.

- National Institute of Standards and Technology. Gaithersburg, Maryland. March 31, 2000.
- The International Conference on Integrity, Reliability and Failure (IRF), Porto, Portugal, July 19 - 22, 1999. (***Keynote Lecture***)
- Department of Mechanical Engineering, Carnegie Mellon University, Pittsburgh, PA, February 5, 1999.
- Sixth Pan American Congress of Applied Mechanics, PACAM VI, Rio de Janeiro, Brazil, January 4-8, 1999.
- CIMTEC'98, 9th International Conference on Modern Materials & Technologies, World Ceramic Congress and Forum on New Materials, Florence, Italy, June 14 – 19, 1998.
- CSME Forum 1998, The Canadian Society for Mechanical Engineering, Ryerson Polytechnic University, Toronto, Ontario, Canada, May 19 – 22, 1998.
- Oak Ridge National Laboratory, Oak Ridge, Tennessee, December 12, 1997.
- AFOSR Mechanics and Materials Program Review, November 19 – 20, 1997, Adolphus Hotel, Dallas Texas.
- 3rd EUROMECH, Solid Mechanics Conference, KTH, Royal Institute of Technology, Stockholm, Sweden, August 19-22, 1997.
- University of Luleå, Department of Mechanical Engineering, Solid mechanics Group, Luleå, Sweden, August 15, 1997.
- The 1997 Joint American Society of Mechanical Engineers (ASME), American Society of Civil Engineers (ASCE), Society of Engineering Science (SES) Summer Meeting, June 29 - July 2, 1997, Northwestern University, Evanston, IL.
- The Ninth International Conference on Fracture, April 1-5, 1997, Sydney, Australia. (***Keynote Lecture***)
- Fifth Pan American Congress of Applied Mechanics, PACAM V, San Juan, Puerto Rico, January 2-4, 1997.
- Symposium on Durability and Damage Tolerance of Composites - 1996 at International Mechanical Engineering Congress and Exposition, Atlanta, GA, November 17 - 22, 1996.
- Structural Materials and Processing Sciences, Advanced Technology and Development Center, Northrop Grumman, Bethpage, NY, August 2, 1996.
- Joint Applied Mechanics and Materials Summer Conference, The Johns Hopkins University,Baltimore, MD, June 12-14, 1996.
- Northwestern University, School of Engineering, Mechanics Colloquium. Evanston, IL, April 26, 1996.
- Northrop Grumman, Advanced Technology and Development Center, Bethpage, NY, February 9, 1996.
- Brown University, Division of Engineering, Providence, RI. October 27, 1995.
- Air Force Wright Laboratory, Nonmetallic Materials Division, Wright Paterson Air Force Base, Dayton, Ohio. August 1, 1995.
- Joint Applied Mechanics and Materials Summer Conference, University of California, Los Angeles. June 28 - 30, 1995.
- The Seventh International Congress on Mechanical Behavior of Materials, The Hague, The Netherlands, May 28 - June 2, 1995.

- The Fourth Pan American Congress of Applied Mechanics. Universidad del Salvador, Buenos Aires, Argentina, January 3-6, 1995.

b. Consultative and advisory functions to other laboratories and agencies.

A technical report based on methodology partially developed during this project, "Analysis of Selected Failure Modes in Composite Materials," was produced for Martin Marietta Manned Space Systems.

c. Transitions.

Methods developed in the course of this project will be used for ceramic composite characterization at Advanced Technology Center, Northrop Grumman Corporation, in Low Cost Ceramic Composites program. The contact person: Dr. Philip N. Adler. This contact was developed during the previous year and continued through the current period.

NEW DISCOVERIES, INVENTIONS, OR PATENT DISCLOSURES:

The results of the investigation of failure process in composites evaluated the role of composite design characteristics on composite functionality and the resulting failure resistance potential. The generated data address the effects associated with fiber or particle spacing, the strength of the interfaces, and other factors. These data will be useful for future composite development, and for reliability and life prediction evaluation of composites.

This project did not generate new patents.

HONORS/AWARDS:

The principal investigator, A. A. Rubinstein, was invited to give a Keynote Lecture on the subject of this project at the Ninth International Conference on Fracture, which took place in Sydney, Australia, April 1997.